



REVIEW ARTICLE

TRANSITIONING TO SUSTAINABLE ENERGY: THE PROMISE OF SOLAR POWER – A REVIEW

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ABSTRACT

Over time, the global energy landscape has shifted from localized, experimental systems to complex, interconnected power grids. Understanding the historical trajectory of these developments provides crucial insights into shaping a sustainable energy future. In light of escalating energy demand, environmental degradation and fossil fuel depletion, there is an urgent need to transit toward cleaner, more sustainable sources of electricity. While renewable energy technologies offer promising alternatives, countries like Nigeria face unique challenges in identifying the most viable options for large-scale deployment. This study employs a structured literature review to examine both the historical evolution and current landscape of power generation technologies. The review encompassed conventional systems (e.g., fossil fuels, nuclear) and renewable sources (e.g., hydro, wind, geothermal, solar). Findings show that past power transitions were driven by more than just technological superiority—they were shaped by economic, institutional, and societal factors. Drawing from this, the study identifies solar power as the most promising renewable option for Nigeria, due to its abundant sunlight, declining costs, and ease of deployment across diverse locations. Compared to wind, tidal, and geothermal energy, solar presents a more practical and scalable solution for off-grid and rural electrification. This insight is reinforced by historical parallels, such as the role of complementary innovations and institutional support in the dominance of alternating current power systems. Solar power stands out as Nigeria's most feasible pathway toward sustainable and resilient energy development. Lessons from historical power transitions highlight the importance of aligning technological innovation with supportive policy, infrastructure, and public engagement. As the country navigates its energy future, prioritizing solar investment and integration will be vital for achieving environmental sustainability, economic growth, and long-term energy security.

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1.0 Introduction

1.1 Evolutionary Trajectory of Electrical Power Generation

The evolution of electrical power generation represents one of humanity's most transformative technological revolutions, fundamentally reshaping society's capabilities and structures. While the historical foundations laid by pioneers such as Galvani, Volta, and Ampere established the scientific principles of electricity, contemporary power systems have undergone radical transformation through successive waves of innovation (Black, 2018). The energy sector now finds itself at a pivotal crossroad, facing intense debate over a potential globally coordinated shift away from fossil fuel-based infrastructures (Stirling, 2014). The transition from experimental demonstrations to industrial-scale implementation has been marked by technological breakthroughs, shifting economic paradigms, and evolving environmental considerations.

Modern scholarship has recontextualized the pivotal "battle of the currents" beyond the Edison-Tesla rivalry narrative toward a more nuanced understanding of how competing technological regimes gain dominance

(Sovacool and Brisbois, 2019). This technological competition represented an early example of what energy transition researchers now recognize as "sociotechnical regime shifts" where multiple factors—including technological superiority, economic interests, institutional frameworks, and cultural acceptance—collectively determine adoption patterns. The eventual triumph of alternating current (AC) systems over direct current (DC) established a technological trajectory that shaped power systems development for over a century.

Edison's Pearl Street station not only represented technological innovation but established new business models and regulatory frameworks that defined modern utility structures. The emergence of long-distance transmission capabilities fundamentally altered the geographic relationships between energy production and consumption, enabling new patterns of industrial development and urbanization that continue to characterize modern energy landscapes (Bridge *et al.*, 2021).

Contemporary research emphasizes that electrical system development follows non-linear innovation pathways. While Thury's series-connected DC systems represented an important technological milestone, their eventual obsolescence illustrates what innovation scholars' term "technological lock-out"—where superior technical solutions may fail against alternatives with stronger institutional support and network effects. The persistence of AC dominance despite its technical limitations compared to modern high voltage direct current (HVDC) illustrates the path dependency that characterizes large-scale infrastructure systems.

The three-phase transmission breakthrough of the 1890s has been recognized as a classic example of "innovation clustering," where multiple complementary technologies (polyphase generators, transformers, and motors) converged to create system-level benefits exceeding individual components. Modern energy transition research draws parallels between this historical development and contemporary renewable energy integration challenges, where similar technological co-evolution is required for system transformation.

1.2 Importance of Electrical Power in Modern Society

Electrical power serves as the backbone of modern society, fundamentally transforming every aspect of human life. It provides energy for homes, businesses, and industries, drives technological advancements, stimulates economic growth, and enhances quality of life. By leveraging the ability to store and direct electric charges, electricity can be harnessed in countless ways to meet diverse human needs. In the 21st century, electricity is indispensable across various sectors. Industrial production depends on it for enhanced efficiency and productivity. As shown in Figure 1, global gross electricity generation has steadily increased in response to population growth (IEA, 2025). This rising demand underscores the urgent need for a transition to more sustainable energy sources, ensuring a reliable and environmentally friendly energy supply for the future.

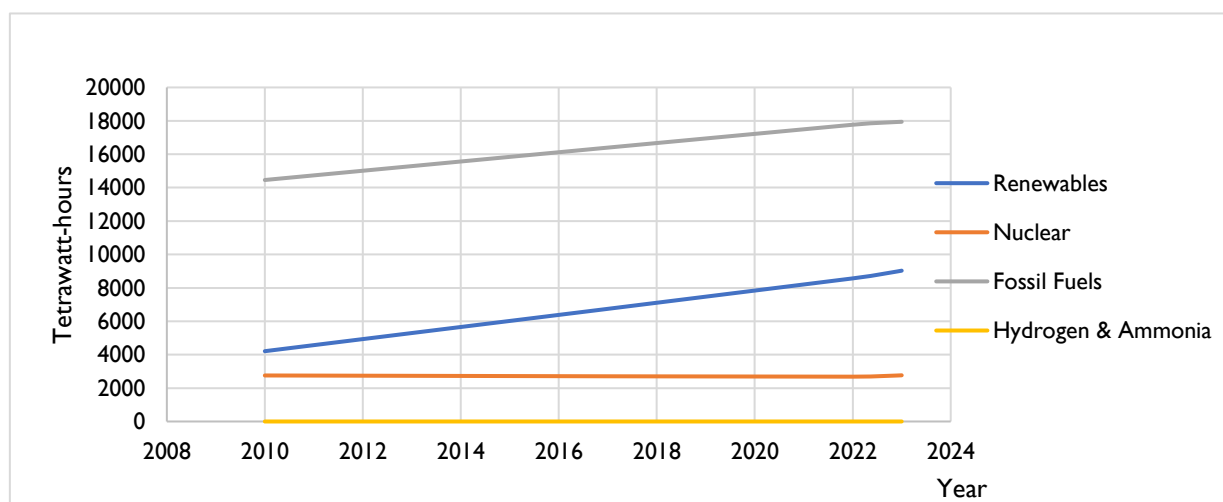


Figure 1: Gross Electricity Generation by Sector (IEA, 2025)

1.3 Overview of the Review's Scope and Objectives

This review aims to offer a comprehensive understanding of electrical power generation, exploring its historical roots and future prospects. The review's objectives are to:

- Trace the historical evolution of electrical power generation.

- Examine various sources of electrical power and their societal and environmental impacts.
- Review lessons for renewable transition from historical power evolution

2. Historical Development of Electrical Power Generation

2.1 Early Discoveries in Electricity and Magnetism

The history of electricity dates back to ancient times, with the earliest known observations recorded by the Greeks. Around 600 BCE, Thales of Miletus discovered that rubbing resin caused it to attract light objects like feathers, a phenomenon now known as static electricity (Iversen and Lacks, 2012). This marked humanity's first step toward understanding electrical phenomena. Other ancient civilizations, such as the Greeks and Egyptians, made similar observations, though they lacked the scientific knowledge to explain these effects (Hardy, 2023).

The scientific study of electricity began to accelerate in the 17th and 18th centuries with key discoveries. In 1600, William Gilbert coined the term "electricity" in his work "De Magnete", initiating its formal study (Gregersen, 2011). In 1752, Benjamin Franklin's famous kite experiment showed the electrical nature of lightning when he successfully charged a Leyden jar from a kite string during a thunderstorm (Sharlin and Meyer, 1972).

In the 19th century, progress continued with Alessandro Volta's invention of the electrophorus in 1775, a device that produced static electricity. It consisted of a metallic disk with an insulating handle that could generate and store an electrical charge through friction. The electrophorus proved useful for generating electricity with minimal effort (Sharlin and Meyer, 1972). In 1820, Danish physicist Hans Christian Oersted discovered electromagnetism, showing that electric currents create magnetic fields by observing how a current passing through a wire caused a nearby compass needle to move (Gregersen, 2011). A decade later, in 1831, Michael Faraday discovered electromagnetic induction, the principle behind modern electrical generators (Purcell, 2011). These breakthroughs laid the foundation for the practical use of electricity and the development of modern power generation technologies.

2.2 The Industrial Revolution and the Dawn of Electrical Power

Michael Faraday's discovery of electromagnetic induction led to the invention of the first dynamos—early electrical generators that demonstrated the practical conversion of mechanical energy into electrical energy.

Despite earlier contributions by physicists like Franz Neumann and Wilhelm Weber, a general law of electromagnetic induction within a Lagrangian framework was not established until James Clerk Maxwell's "Treatise", in which he remarkably derived his theory using the velocity of an elementary circuit element—rather than charge motion—at a time when electrical current was still viewed as a kinetic process (Giuliani, 2021).

In 1873, Zenobe Gramme developed a functional electric generator that efficiently converted rotary motion into electric power. Earlier generators often overheated due to the armature's movement, but Gramme's innovation solved this issue, making power generation more practical (Forrester, 2016). This breakthrough was soon followed by other key developments, including Charles F. Brush's 1878 brush arc lamp dynamo, which powered street lighting, and "Thomas Edison's Pearl Street Station", the world's first central power plant, opened in 1882. This historic station in New York City operated with six engine-dynamo sets and supplied electricity to 59 customers over a 1.5-kilometer (km) radius using underground cables (Singh, 2010).

In 1889, the United States saw its first long-distance transmission of DC electricity at Willamette Falls Station in Oregon. However, a flood in 1890 destroyed the station, paving the way for the installation of experimental AC generators by Westinghouse. By 1896, the first AC generation and transmission system at Niagara Falls was completed, also using Westinghouse equipment (de Andrade and de Leao, 2012). These developments contributed to the rapid adoption of AC over DC. By the late 19th century, the United States had "202 Edison DC central stations and 323 Westinghouse AC stations" (Allerhand, 2017). These early power stations laid the foundation for the modern electrical utility industry, transforming society through widespread electrification.

3. Major Sources of Electrical Power Generation

3.1 Fossil Fuel-Based Generation

A thermal power plant, or heat generation station, converts heat energy into electrical power. In these stations, steam or heat is used to transform heat energy into mechanical energy, which then drives the generation of electricity (Varshney, 2017). Coal, oil, and natural gas-fired plants are categorized as thermal power stations. With most modern countries having fully developed hydraulic resources, increasing reliance is placed on thermal and nuclear power stations to meet growing energy demands.

Thermal power plants generate electricity by utilizing heat from the combustion of fossil fuels such as oil, coal or natural gas. To optimize economic efficiency, these plants typically have capacities ranging from 200 megawatts (MW) to 1500 megawatts (MW). The sheer complexity and size of such installations become apparent when observed in person.

Thermal power plants are commonly located near rivers or lakes to access the substantial cooling water needed to condense steam after it exits the turbines (Wildi, 2006). However, their efficiency remains relatively low due to the inherent limitations of turbines in converting heat into mechanical energy.

In practice, even the most efficient steam turbines achieve efficiencies of only around 45%, meaning that 55% of thermal energy is lost during the conversion process. This significant heat loss presents one of the major challenges in operating thermal power stations (Wildi, 2006).

Thermal stations' environmental impact is a growing concern due to the pollutants released from burning fossil fuels. The main combustion byproducts are water, carbon dioxide and sulfur dioxide. While carbon dioxide and water have minimal immediate environmental effects, sulfur dioxide can lead to acid rain. Dust and fly ash are other pollutants. Natural gas, however, produces only carbon dioxide and water, making it the preferred fuel when reducing atmospheric pollution is essential. A clear drawback of fossil fuels is their finite nature, making them an unsustainable long-term option for power generation as seen in Table I on page 20—especially for countries like Nigeria that rely heavily on them.

3.1.1 Coal-Fired Power Plants

Coal remains a crucial source of electricity generation despite the environmental challenges it presents. As the most widely distributed and abundant fossil fuel, coal-fired power generation accounts for about 45% of electricity in the United States, 40% in Germany, and roughly 25% in Japan. In China, the share is approximately 80%, while in India and Serbia, it is around 70% (Lakovic et al., 2015).

A conventional coal-fired thermal power plant operates using a boiler-turbine-generator system. Coal combustion in the furnace generates heat, which warms the feed water inside the boiler drum, producing steam. This steam is directed to turbines, where its kinetic energy is converted into mechanical energy. A generator connected to the turbine then transforms this mechanical energy into electrical energy. Efficient combustion requires precise control of fuel and air flow rates, as well as careful management of feed water flow, to optimize power generation (Shajahan et al., 2018). While coal-fired power generation offers several advantages, including the availability of coal as a fuel source and its ability to provide reliable base load power, it also has significant environmental impacts. As noted by Bhagwan (2022), thermal power plants contribute to pollution through emissions of sulfur oxides, nitrogen oxides, and particulate matter, which can disperse over a 25 km radius.

3.1.2 Natural Gas Power Plants

Electrical energy can be generated from hydrocarbon fuels such as coal, oil, and natural gas, as well as from renewable sources like solar, wind, and geothermal energy. The role of natural gas in power generation is expected to expand over the next two decades as it continues to replace coal. However, by 2050, its usage may decline due to the accelerated shift toward renewable energy. Natural gas power generation offers several advantages over coal, including a 45% reduction in carbon dioxide emissions and significantly lower sulfur, mercury, and particulate emissions (Thirion and Steyn, 2021). Furthermore, modern combined cycle power plants can achieve efficiencies of up to 64%, far surpassing the roughly 40% efficiency of traditional steam turbine plants (Thirion and Steyn, 2021). By 2019, gas turbine combined cycle plants had surpassed coal-fired plants in generating capacity within the United States (Thirion and Steyn, 2021).

In a gas turbine setup, processed natural gas is transported via pipelines to the plant, where it combines with compressed air in the compressor and undergoes combustion in the combustion chamber. The resulting high-temperature gases produce the energy required for electricity generation, with the output directly corresponding to the energy released from burning natural gas (Mathias and Olusegun, 2020). It is important to note that natural gas still produces substantial carbon dioxide emissions, contributing to greenhouse gas levels. Additionally, the price of natural gas can be volatile, creating economic uncertainty in its use for power generation.

3.2 Nuclear Power Generation

Nuclear power plants generate electricity by harnessing the heat produced from nuclear fission. These plants depend on complex cooling and safety systems for proper operation. These plants offer the potential to generate vast amounts of energy in a single plant, unlike coal-fired plants, which release a range of harmful chemicals into the atmosphere such as nitrogen oxides, mercury, particulate matter, etc. With the depletion of fossil fuels raising concerns about future energy scarcity, nuclear energy remains a vital low-carbon, clean energy source that is expected to grow (Sadekin *et al.*, 2019). Uranium, a primary fuel source for nuclear power plants, is mined and processed into uranium dioxide (UO_2). Natural UO_2 contains a small amount of the fissile isotope ^{235}U , which is enriched to make it suitable for nuclear reactors. This enrichment process results in byproducts like $^{238}\text{UO}_2$, which can have additional uses (Wildi, 2006). The first nuclear reactor, constructed under the leadership of Enrico Fermi in 1942, marked a pivotal moment in nuclear science by achieving the first controlled nuclear chain reaction, laying the groundwork for modern nuclear power generation (Zohuri and McDaniel, 2015).

A nuclear power station is similar to a thermal power station, except that a nuclear reactor replaces the boiler. The reactor contains fissile material that generates heat, and like conventional thermal stations, the power generation efficiency is around 30 to 40 percent (Terzi and Kurt, 2018). Nuclear plants are typically located near large water sources, or in places where cooling towers are used to manage heat.

Significant challenges remain with nuclear power generation, including the high initial capital investment, the complexity of managing radioactive waste, and ongoing public safety concerns, particularly after notable nuclear accidents. These factors continue to influence the broader adoption of nuclear energy and gives it a low suitability for Nigeria as seen in Table 1 on page 20.

3.3 Hydropower

The world's first hydropower project was established in 1878 to illuminate a single lamp in a home in Cragside, Northumberland, England. Four years later, the first commercial hydropower plant became operational in Wisconsin, USA (Sharma *et al.*, 2021). Today, over 160 nations use hydropower to generate electricity (Benneth *et al.*, 2023). Hydropower, which harnesses the energy of flowing water, is broadly classified into two main types: hydroelectric systems and tidal power. Hydroelectric systems include conventional dams, run-of-river installations that generate power without large reservoirs, and pumped-storage facilities, which store energy for later use. Tidal power, on the other hand, captures energy from tidal movements. However, hydropower does have drawbacks, including environmental impacts on river ecosystems, dependency on rainfall and water availability, and displacement of communities during large-scale projects.

3.3.1 Hydroelectric Generation

Hydroelectric power, the most commonly used renewable energy source, harnesses the gravitational force of falling or flowing water to generate electricity. Once in operation, hydroelectric plants produce no direct waste and emit significantly lower carbon dioxide levels compared to fossil-fuel power stations. The amount of electricity generated depends on two key factors: the hydraulic head, which is the elevation difference between the reservoir and the discharge point, and the rate of water flow. The amount of energy (E), released when an object of mass (m) falls a height (h) in a gravitational acceleration (g) is given by (Wildi, 2006):

$$E = mgh \quad 1$$

Hydroelectric generation methods can be categorized into four types: conventional, pumped-storage, in-stream, and run-of-the-river (Karre *et al.*, 2022). Traditional hydropower systems utilize dams to capture the potential energy of stored water, which is then used to drive turbines and generators. The amount of energy generated is determined by the volume of water and the elevation difference, or head, between the water source and its discharge point. A penstock channels water to the turbines while maintaining the pressure from

the head (Moniruzzaman, 2019). Pumped-storage plants, which balance load demand, move water between reservoirs at different elevations to generate electricity during peak demand periods. These plants are cost-effective because they reduce reliance on peaking power plants, but the initial construction costs are high.

Run-of-the-river plants generate power without large water reservoirs, relying instead on natural river flow. Water is diverted through pipes to turbines and returned to the river downstream. These projects are considered more environmentally friendly than conventional hydroelectric setups as they cause less flooding and emit fewer greenhouse gases. However, run-of-the-river plants are less reliable because they cannot store energy to meet demand fluctuations. In-stream hydropower systems, similar to run-of-the-river setups, place turbines directly within riverbeds or dams, utilizing existing waterways to generate electricity. These systems may also function with bi-directional tidal flows (Karre *et al.*, 2022).

3.3.2 Tidal Power

Tidal power plants harness the predictable rise and fall of ocean tides, making them a highly reliable renewable energy source. Energy can be extracted from tides in two primary ways: by utilizing tidal barrages, which store seawater and capture its potential energy, or by employing tidal stream generators, which harness the kinetic energy of moving water, similar to wind turbines (Navya *et al.*, 2021).

Tidal stream generators function like underwater wind turbines, using fast-moving tidal currents to drive turbines and generate electricity. These generators can be installed in naturally occurring channels, such as harbors and lagoons, where water moves swiftly (Chauhan *et al.*, 2015). They come in two main types: horizontal-axis turbines, where the blades rotate parallel to the water flow, and vertical-axis turbines, where the blades rotate perpendicular to the water flow (Zainol *et al.*, 2017). Due to their lower costs and reduced environmental impact, tidal stream generators are becoming increasingly popular compared to traditional tidal barrages.

Tidal power has several drawbacks that limit its widespread adoption. One major issue is the high initial cost of constructing tidal barrages, turbines, and related infrastructure. Additionally, tidal power plants can disrupt marine ecosystems, altering tidal patterns and affecting aquatic life. Suitable locations for tidal energy generation are limited, as only coastal areas with strong tidal ranges and water flow can support such projects. Another challenge is the intermittent nature of energy production, as tidal cycles result in power generation only during high and low tides, creating gaps in supply. Maintenance is also a concern, as the harsh marine environment causes corrosion and biofouling, increasing operational costs. Furthermore, large tidal structures may interfere with shipping routes and fishing activities, creating potential navigational challenges. These factors make tidal power less widely adopted compared to other renewable energy sources.

3.4 Wind Power

Wind energy converts the kinetic energy of moving air into electricity through wind turbines, which can be deployed on both land and at sea. These turbines, especially large utility and offshore models, are typically located far from population centers, generating energy for widespread use (Aziz *et al.*, 2020). Wind energy is renewable, has no fuel costs or emissions during operation, and has become increasingly cost-competitive. Wind turbines operate efficiently within a wind speed range of 3.5 to 25 m/s (Radzka *et al.*, 2019). Despite its advantages, wind power faces challenges such as its intermittent nature, potential impacts on wildlife (particularly birds and bats), and visual and noise concerns.

Wind results from air movement driven by pressure differences caused by the earth's uneven heating by the sun. The kinetic energy of this moving air can be transformed into mechanical energy using wind turbines, which feature blades extending from a central hub. When wind pushes against the blades, they rotate, generating mechanical energy that is converted into electricity through a generator. Pitch and yaw controls adjust the turbine's orientation to optimize performance.

Globally, wind power is the second most widely deployed renewable energy source after hydropower, with 51GW of capacity added in 2018, second only to solar energy (Eicke *et al.*, 2022). Although there are no fundamental technical barriers to wind power integration, maintaining grid stability becomes crucial as capacity increases. Wind energy systems convert wind's kinetic energy into electricity through multiple stages. The efficiency of wind energy conversion depends on factors such as wind speed, the rotor's swept area, and the efficiency of the rotor and generator. Wind power output is highly sensitive to wind speed, increasing proportionally to the cube of wind velocity. A small rise in wind speed results in a significant boost in power generation. The power output is also proportional to the turbine's swept area, which is defined by the

diameter of the rotating blades. A wind energy system consists of key components, including the aero turbine, mechanical interface, electric generator, and controller.

Wind turbines are classed based on the axis of rotation into two main types: horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). HAWTs are the most widely used, featuring a small number of aerodynamically optimized blades that can be regulated through pitch control or stall regulation. These turbines range in capacity from small 10kW units to large multi-megawatt systems, with some reaching up to 5MW. For example, a 10kW turbine can supply enough electricity to power an average household in the U.S. or several rural villages in Nigeria (Garba and Al-Amin, 2014). They are typically configured with three blades, a design that balances efficiency and stability (Tywoniuk and Skorupka, 2018).

VAWTs, while less common, have a simpler structure and do not depend on wind direction. The Darrieus type, in particular, comes in several designs, such as the H-Darrieus and Eggbeater models, and often requires an auxiliary system like a Savonius rotor to start (Wagner and Mathur, 2009). Wind energy offers several drawbacks, such as fluctuating energy availability, the need for auxiliary storage devices like batteries, noise concerns, space requirements, and the complexity and weight of the systems due to the high towers required.

3.5 Geothermal Power

Geothermal energy is considered a renewable resource, with high-pressure steam from beneath the Earth's surface serving as the primary heat source. As the earth's temperature increases with depth, reaching around 180°C at significant depths, water is commonly used as a medium to extract this heat. At a depth of about 10km, the temperature can rise to approximately 200°C. Rainwater or other surface water seeps into the earth's deeper layers through the highly permeable and fractured crust, where it absorbs heat from the surrounding rocks. Heat transfer occurs through both conduction and convection, with convection being highly efficient in areas with fractured rocks and circulating fluids. These heated fluids, known as hydrothermal resources, can be accessed by drilling wells, allowing the hot water or steam to be brought to the surface for direct use or for electricity generation.

In regions with particularly high geothermal activity, fluids can exceed temperatures of 300°C and may exist as either water or steam depending on the pressure. These fluids, when extracted, can be used in various geothermal power plants or directly for heating purposes. Ground-source heat pumps, commonly used for extracting or storing heat at shallower depths, are another application of geothermal energy (Chijindu, 2021).

The direct use of geothermal energy generally involves well-established technology and straightforward engineering methods. The most common approach is drilling wells into underground reservoirs of hot water and steam, which are then pumped to the surface for heating buildings and generating electricity (Sharmin et al., 2023). Hydrothermal convective systems are the primary geothermal resources used for generating electric power, and they can be classified into either vapor dominated or liquid dominated fields.

Geothermal power has several disadvantages that limit its broader implementation. One major drawback is the high upfront cost associated with exploration, drilling, and plant construction, making it less economically viable in some regions. Suitable geothermal sites are geographically limited, as only areas with high underground heat activity can effectively generate power. The sustainability of geothermal reservoirs can also be a concern, as excessive extraction without proper management may lead to resource depletion over time. Environmental issues such as land subsidence and the release of harmful gases like hydrogen sulfide and carbon dioxide can pose risks. Additionally, geothermal fluids can be corrosive and contain harmful minerals, requiring proper disposal and treatment to prevent environmental contamination. In some cases, geothermal plants may trigger minor seismic activities, raising concerns about induced earthquakes. These challenges make geothermal power less universally applicable compared to other sources.

3.6 Solar Power

Solar power photovoltaic (PV) systems generate electricity by directly converting sunlight into electrical energy. As an abundant and renewable energy source, solar power emits minimal pollution and can scale from small installations to large utility projects. However, challenges such as intermittent generation, large land requirements for utility-scale installations, and the need for energy storage to ensure continuous power supply remains a major challenge.

Since the oil crisis in the early 1970s, leading nations like the United States, Spain, Germany, Switzerland, France, Italy, and Japan have prioritized solar thermal power generation in their national research and

development agendas (Kushwaha and Kesari, 2022). Over time, these efforts have led to the construction of numerous large-scale solar thermal plants, with more than 20 such plants (each with a capacity exceeding 500 kW) built globally in the past two decades. Several of these are now in commercial operation (Kushwaha and Kesari, 2022). Solar energy is a clean, renewable resource with vast potential to meet global energy demands while addressing social, economic, and environmental concerns (Khajavipour et al., 2021). Solar energy is the most abundant energy source on the earth and can be harnessed through both conventional methods and modern technological advancements, contributing to the reduction of greenhouse gas emissions (Ingole et al., 2020). It is converted into usable power using photovoltaic cells and solar thermal collectors (Kumar et al., 2018). The total solar flux absorbed at sea level is approximately 1.2×10^{17} W, which equates to about 20 MW per person—roughly the output of ten large diesel generators, sufficient to meet the energy needs of a town of 50,000 people (Twidell, 2021).

Solar cells, which convert sunlight into electricity, come in two major forms based on the materials used in their construction. Common materials include “monocrystalline and polycrystalline silicon, cadmium telluride (CdTe), gallium arsenide (GaAs), and indium gallium phosphide (InGaP)”, among others (Sanjay and Saqib, 2020). Crystalline solar cells, particularly monocrystalline and polycrystalline, currently achieve the highest conversion efficiencies among photovoltaic cells (Kumi and Brew-Hammond, 2013). When sunlight hits a solar cell, it causes a phenomenon known as the photoelectric effect, where heat breaks metal bonds, freeing electrons to generate current. The photovoltaic effect, which occurs within the material, is responsible for the electricity produced in solar panels.

Solar power generation in general offers several advantages. The conversion system has no moving parts, making it reliable and low-maintenance. It produces no pollution, has a long operational lifespan and offers very high scalability although the efficiency is between 15 to 22% as seen in Table 1, this continues to improve with continued research and innovation. Since solar energy is free, there are no fuel costs, and the system can handle large power loads. However, the main disadvantage is the high initial cost, partly due to the need for energy storage systems like batteries, as sunlight is not available at night, although research in lunar panels aims to solve this issue.

Table 1: Power Generation Impact and Suitability

Technology	Efficiency (%)	Environmental Impact	Scalability	Cost Trend	Suitability for Nigeria
Fossil Fuels	33 – 45	High (CO ₂ , SO _x , NO _x)	High	Increasing	Unsustainable
Nuclear	30 - 40	Low CO ₂ , High toxic waste	Moderate	Stable/High	Low (infrastructure safety)
Hydropower	35 - 45	Low	Site-specific	Stable	Moderate
Wind	30 - 45	Very Low	Site-dependent	Decreasing	Low (inconsistent wind)
Geothermal	10 - 20	Low	Localized	Stable	Very low (resource limits)
Solar PV	15 - 22	Very Low	Very High	Rapidly decreasing	High
Tidal	20 - 30	Low	Low	High	Not viable in Nigeria

4. Lessons for the Renewable Transition from Historical Power Evolution

Despite a 15% rise in global energy demand over the past decade, the share of fossil fuels in the energy mix declined slightly from 82% in 2013 to 80% in 2023, with clean energy—comprising renewables, nuclear, and low-emission technologies—meeting 40% of the additional demand and projected in the IEA’s “Stated Policies Scenario” (STEPS) to drive fossil fuel consumption to a peak before 2030, though fossil fuels are still expected to supply 58% of energy by 2050, compared to just 10% under the “Net Zero Emissions” (NZE) scenario where renewables provide 90% (IEA, 2025). This trend is illustrated in Figure 2.

The historical evolution of electrical power systems reveals more than just a series of technological advancements—it provides crucial insights into how innovation, infrastructure, and policy interact to shape energy landscapes and accelerate clean energy adoption.

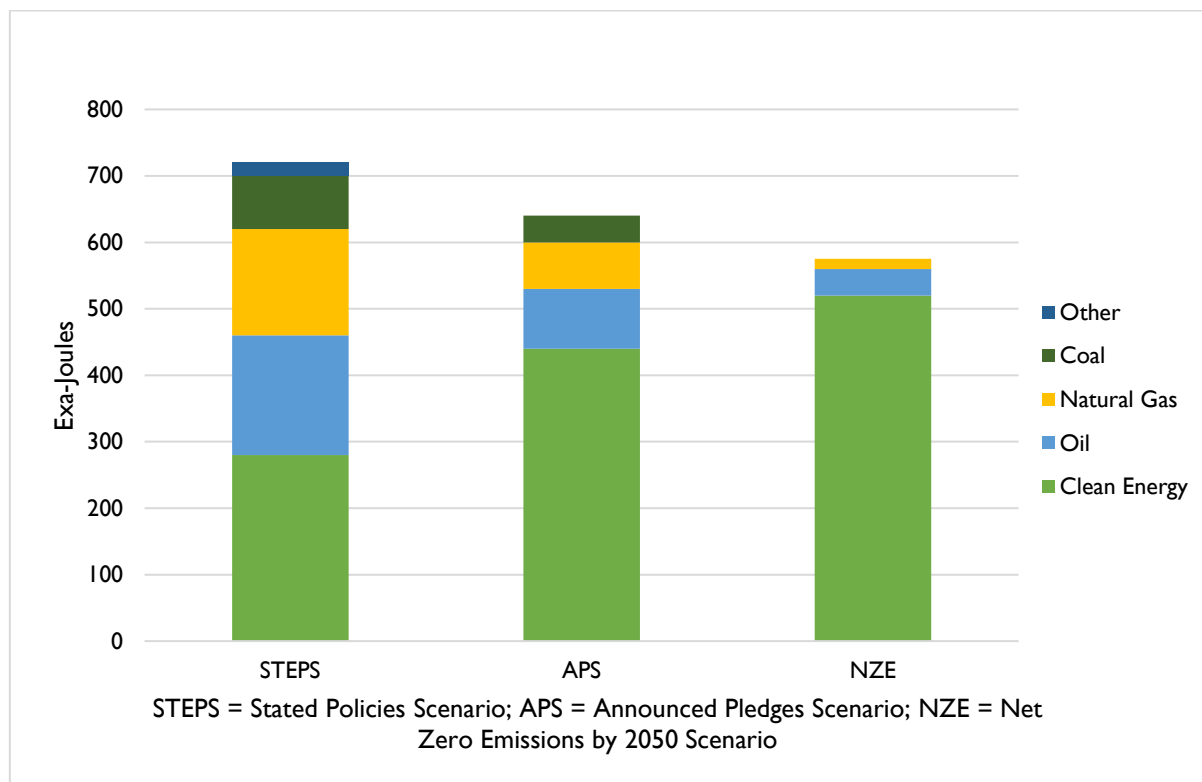


Figure 2: Targeted global energy mix by 2050 (IEA, 2025).

As Nigeria and other nations strive to transition from fossil fuel-based systems to sustainable energy sources, these historical patterns offer valuable lessons, enabling them to avoid past mistakes and effectively accelerate the deployment of clean energy solutions. Following are key lessons for the renewable transition derived from historical power evolution.

- Sociotechnical Factors Drive Adoption, Not Just Technical Merit

The historical dominance of AC over direct DC, despite early DC advantages, demonstrates that the success of a technology depends on a confluence of factors: institutional support, economic viability, compatibility with existing infrastructure, and public perception. In today's context, this suggests that renewable technologies will not win adoption solely by offering better efficiency or environmental benefits—they must be integrated into a broader system that supports their use. In Nigeria, for instance, while various renewable technologies (such as wind, biomass, and hydropower) have shown technical promise, they often face logistical and policy-related barriers that inhibit widespread deployment.

- Innovation Clusters Accelerate System Transformation

The emergence of three-phase AC systems in the 1890s was enabled by the convergence of generators, transformers, and motors designed to work in tandem—a process known as “innovation clustering.” Similarly, the success of solar energy in modern power systems hinges not only on panel efficiency but also on the development of complementary technologies such as storage batteries, smart inverters, and decentralized grid architectures. Nigeria's solar potential is immense, particularly in the northern regions, where solar irradiance is consistently high. By investing in these enabling technologies and creating integrated solar ecosystems, Nigeria can leapfrog many of the structural limitations that have slowed other forms of electrification.

- Technological Lock-Out Can Be Avoided Through Flexibility

The historical marginalization of Thury's HVDC system exemplifies how early infrastructure choices can lock systems into suboptimal pathways. Today, many energy systems suffer from similar lock-ins, such as centralized grid designs that do not support distributed generation. For Nigeria, a key lesson is the importance of flexibility—both in policy and technical design. Supporting modular, off-grid solar installations in rural communities can provide rapid and scalable electrification without waiting for large-scale infrastructure upgrades.

- Solar Energy as Nigeria's Optimal Renewable Pathway

Among all renewable sources, solar energy presents the most viable and strategic option for Nigeria. Unlike hydropower, which is vulnerable to climate variability and regional disputes, or wind power, which is geographically constrained, solar energy is abundant, widely distributable, and rapidly declining in cost. Moreover, the decentralized nature of solar systems aligns well with Nigeria's need to expand energy access to underserved rural populations. With the right combination of policy incentives, public-private partnerships, and local capacity building, solar power can become the backbone of Nigeria's sustainable energy transition.

5. Conclusion

This review traced the evolution of electrical power generation and highlighted how economic, institutional, and technological factors have shaped energy transitions. Today, as clean energy gains momentum, scenarios like the IEA's Net Zero Emissions (NZE) envision renewables meeting up to 90% of global demand by 2050, signaling a clear shift from fossil fuels. For Nigeria, where resource constraints and environmental concerns converge, solar energy stands out as the most viable path forward due to its low environmental impact, scalability, and adaptability to both urban and off-grid settings. While solar offers transformative potential, its success hinges on integrated efforts—investment in storage, smart grids, and supportive policies—much like historical shifts that required systemic coordination. By embedding solar in a broader development strategy and learning from past transitions, Nigeria can enhance energy access, drive economic growth, and meet climate goals. Unlocking this potential will require bold leadership, strategic investment, and institutional innovation.

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